Experimental Investigation of an Innovative HVAC System with Integrated PVT and PCM Thermal Storage for a Net-Zero Energy Retrofitted House

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ABSTRACT

This paper presents the experimental investigation of a novel solar assisted HVAC system developed for the Team UOW Solar Decathlon house, the overall winner of the Solar Decathlon China 2013 competition. This novel HVAC system consists of an air based photovoltaic-thermal (PVT) system and a phase change material (PCM) thermal storage unit integrated with a ducted system with a reverse-cycle heat pump. The system has been designed for operation during both winter and summer, using daytime solar radiation and night sky radiative cooling to increase the energy efficiency of the air-conditioning system. The PVT system can exchange heat with the PCM thermal storage unit, and the stored heat can be used to condition the space or precondition the air before entering the air handling unit (AHU). This system is controlled by a residential type building management and control system (BMCS). Experimental data has been collected through the BMCS system under typical working conditions. The various operational modes in which the system operates and the key controlled variables are presented. This paper focuses on the optimization and operation of the PVT working modes and the results from experimental tests are discussed. The experiments were carried out at the Innovation Campus, University of Wollongong, on the reassembled house after the Solar Decathlon competition held in Datong, China. The performance results presented represent the first experience of this system in Australia. The experiments show that the PVT system can provide a significant amount of useful heating to the house or to the PCM thermal storage unit at a considerably higher efficiency than a normal air conditioning system, with an average COP of 13.5 when heating the house and 10.7 when heating the box, in different weather conditions.

INTRODUCTION

Every year only approximately 1 to 2 percent of the Australian residential building stock is replaced by or added to by new buildings (Ma et al. 2012). Many of the existing houses built after the Second World War in Australia were timber-framed houses, clad in fibre-cement, and were hence colloquially named 'fibro' houses. These buildings generally exhibit poor thermal performance and low energy efficiency, which makes them a suitable target for energy efficient upgrades.

Under the auspices of the UOW Sustainable Buildings Research Centre (SBRC) a student/staff team (Team UOW) was formed with members drawn from both the University of Wollongong and TAFE NSW Illawarra Institute, aiming to demonstrate how to bring a 'fibro' home to net zero energy performance while also transforming the level of thermal comfort and overall sustainability performance through the development and application of different retrofit technologies. Team UOW wasthe first team in the history of Solar Decathlon competitions to demonstrate how to upgrade and retrofit an existing building rather than designing a new building from scratch. This approach proved to be extremely successful

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and Team UOW subsequently won the Solar Decathlon China 2013 competition with the highest overall score in the history of Solar Decathlon competitions (which first ran in the USA in 2002). One of the key targets in this retrofit project was to achieve net-zero energy consumption, i.e. the grid-connected building generates more renewable energy on-site than it imports from the grid over the course of a year, while trying to minimize the amount of renewable energy generation required, by utilizing high energy efficient active and passive building systems. To achieve this target different retrofitting techniques have been applied to reduce the demand of the building including upgrading the envelope, glazing, shading systems and using natural ventilation when possible.

Increasing the energy efficiency of heating, ventilation and air conditioning (HVAC) systems is a key focus of current research (Jazizadeh et al. 2014, Ma and Wang 2011). Among various renewable energy technologies, photovoltaic-thermal (PVT) systems have shown potential for the market (Chow 2010). Most of the PVT systems use water or air as a working fluid. Air systems provide a simple and economical solution to cool the solar panels and at the same time generate useful heating for the air stream, which can be used for air-conditioning purposes, increasing the overall efficiency of the system. Various solar assisted HVAC systems have been investigated with and without energy storage, and a range of different types of thermal energy storage systems to offset the demand of buildings (Pantic et al. 2010, Ortiz et al. 2010, Chen et al. 2010). In particular, thermal energy storage has been considered as an important alternative to solve the problem of mismatch between the energy generation and the building demand, when solar energy systems are implemented in buildings (Al-Abidi et al. 2012). Thermal energy storage can be categorized according to the type of materials used to store the energy, dependent on latent or sensible heat is used to store the energy or the methodology used to store the energy in the storage medium (ASHRAE HandBook 2008) Latent heat thermal energy storage is attractive because of its high storage capacity per unit of volume or mass, particularly compared to conventional sensible heat storage, and the fact that the temperature remains almost constant during the phase change. The use of active storage has been proven to be effective through the experience gained in different applications (Kenisarin and Mahkamov 2007), where it has been used to improve the efficiency of HVAC systems. The solar photovoltaic–thermal (PVT) assisted HVAC system described in this paper is one of these retrofitting options and it consists of an air based PVT system and a phase change material (PCM) thermal storage unit integrated in a ducted system with a reverse-cycle heat pump.

HVAC SYSTEM DESCRIPTION

Figure 1 presents the innovative and effective solar PVT-assisted HVAC system, developed for the Team UOW Solar Decathlon house. The air delivery system of this house is based on a combination of flexible and rigid ductwork, which allows an effective functional integration of the different "energy components" of the system including the PVT system, the PCM thermal energy storage unit and a standard type of air conditioning system, with an outdoor condensing unit and an indoor air handling unit (AHU).

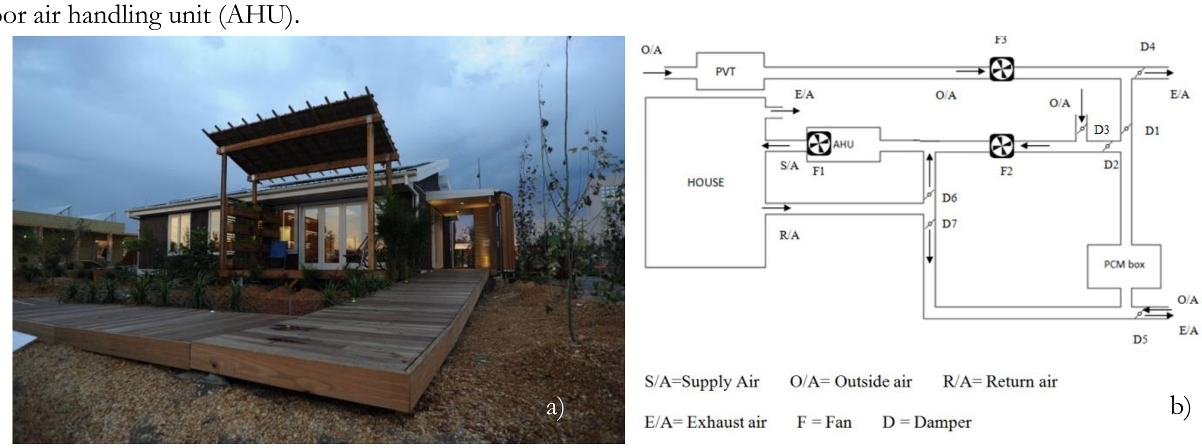

Figure 1: *a) Team UOW Solar Decathlon house and b) HVAC schematic.*

Figure 1 b is a schematic of the HVAC system developed in this project. This system integrates the different components using a ducted air distribution system, in which variable speed fans are used to control the air flow rate and dampers are used to change and regulate the airflow paths in and out of the system. The use of air in the PVT collector as a working fluid has been dictated by the need of the system to be simply retrofitted to an existing house, with low maintenance requirements and simple integration with a ducted air-conditioning system. The PVT collector is formed by flexible thin-film CIGS PV panels glued to a metal flashing that bridges the 'valleys' of the roof sheeting. Air can therefore flow in the duct between the underside of the PV panels/flashing and the roof sheeting and exchange heat with the panels. The thermal generation of the PVT has generally, considering Sydney weather conditions, a significant offset with the demand of the building. For this reason an active thermal storage unit has been included in the design of the HVAC system, and PCM with the melting temperature of 22˚C (71.6˚F), was selected as the preferred material because it can store large latent heat energy at a relatively constant phase-change temperature. To ensure the system always meets the energy demand of the house and good thermal comfort of the indoor space is maintained, a standard reverse-cycle air conditioning system with an outdoor condensing unit and an indoor air handling unit (AHU) is integrated into the system. The whole system is controlled through a residential type of BMCS with a programmable logic controller.

HVAC SYSTEM OPERATING MODES AND OPTIMIZATION

The HVAC system in the Team UOW Solar Decathlon house is managed by a sophisticated control system that controls the operation and interaction of the PVT, PCM storage unit and conventional AHU, and also controls/uses all other key functions in the building, including weather station, lighting, etc. This has been developed using off the shelf products and customized logic. This section outlines the operating modes in which the BMCS system is designed to operate the HVAC system, that consists in three different Conditioning Modes and two PVT modes. It should be noted that the high-level control system is not designed to independently manage humidity in the house, as in the case for standard residential HVAC applications.

Conditioning Modes

The various operational modes that the system can operate in based on the indoor and outdoor measured conditions are shown in Figure 2. . Depending on the indoor conditions, the system can either work in natural ventilation mode through automatically controlling the opening of high level windows, or work in forced mechanical heating or cooling mode. In the mechanical heating and cooling mode, the system can operate in three different sub-modes:

1. *Direct Photovoltaic-Thermal Supply.* If the generation of heating during daytime or cooling during night time (night sky radiative cooling) occurs at the same time as the demand, then heated air/cooled air from the PVT system is directed into the house until the demand is matched. If the demand is higher than the energy extracted from the PVT system, the AHU will cover the remaining heating/cooling requirement.
2. *Supply Air Preconditioned Through Phase Change Material.* In this case, if thermal energy is available in the PCM store the mixture of return air and fresh air will be preconditioned by the PCM store, increasing or decreasing the supply air temperature. If the demand is higher than the energy extracted from the PCM storage unit, the AHU will cover the remaining heating/cooling requirement.
3. *Normal Heating and Cooling Mode.* If there is no PVT thermal generation and no thermal energy stored in the PCM, the AHU will supply the heating or the cooling required.

These modes are presented in Figure 2a.

PVT Modes

If no interfering operating mode is activated, the system can operate in two other modes (Figure 2b):

1. *PCM Charging.* If there is no demand from the house, the PCM unit is not fully charged and it is convenient to

charge it, the PVT system will charge the PCM unit.

2. *PVT Exhaust.* In case the increase in electrical generation of the solar panels due to their temperature decrease is higher than the energy used by the fan, the air can be drawn underneath the PV panels and exhausted directly to ambient.

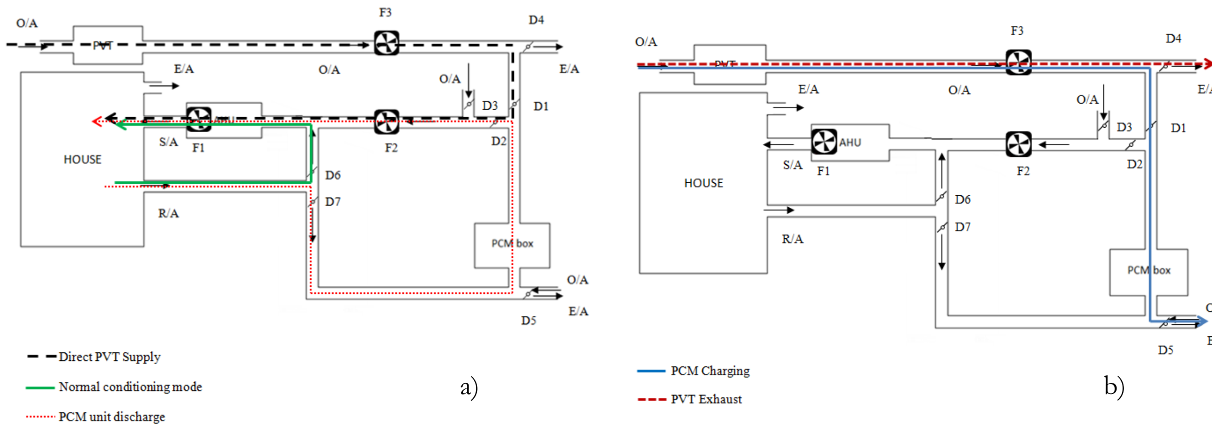

Figure 2: *a) HVAC system conditioning modes and b) HVAC system PVT modes.*

Optimization of Operation Modes

The system is controlled with a rule-based logic that tries to optimize the system at each time step. The system employs an analytical equation to calculate the supply air temperature to the house, depending on the working mode selected by the logic. The normal air-conditioning system is controlled with a relay, when therefore is only turned on and off and its operation is not optimized. For the other working modes, the controlled variable subject to optimization is the air mass flow rate moved into the system by the fans. The consumption of the fans has been identified at discrete speed levels (Figure 3) for each working mode. The current cost function C is then calculated for each speed level i:

$$C_i = P_{th,i} - \alpha \cdot P_{el,i} \tag{1}$$

$$P_{th,i} = \dot{V}_i \cdot \rho \cdot c_p \cdot (T_{supply,i} - T_{avg,house}) \tag{2}$$

Where P_{th} is the heat introduced in the building, P_{el} is the electrical power consumption of the fans, α is a coefficient introduced to weight electrical power compared to thermal, $\dot{V}$ is the flow rate, c_p is the specific heat capacity of air at 20°C (68°F) and ρ is the density, T_{supply} is the supply air temperature, and $T_{avg,house}$ is the average temperature of the house.

The fan speed level corresponding to the maximum value of C is then utilized:

$$\bar{m} = max_{i=1,..,n}\, C_i \tag{3}$$

The same procedure is followed to optimize the PCM charging mode, substituting the calculated outlet temperature of the PCM thermal energy storage unit, $T_{opcm,i}$ to $T_{avg,house}$:

$$P_{th,i} = \dot{V}_i \cdot \rho \cdot c_p \cdot (T_{supply,i} - T_{opcm,i}) \tag{4}$$

The cost function is calculated as in (1).

EXPERIMENTAL RESULTS

PVT tests were carried out in Wollongong, Australia, in June 2014. The PVT collector, integrated with the HVAC system of the house, was controlled and monitored through a residential type of building management and control system (BMCS), and all the data points logged with a commercial building type high level controller with one minute sample period. The weather conditions were monitored with a commercial weather station (including ambient temperature, solar radiation and wind speed), and fed through RS232 serial communication to the control unit. Airflow was monitored with air velocity sensors, placed at 1/3 of the diameter on the duct. These sensors have an accuracy of ±0.2 m/s (±0.65 fps) + 3% of measured value. Temperatures in the ducting were measured with digital temperature sensor units of the BMCS with an accuracy of ±0.5°C (±0.9°F) and capable of measuring between -10°C (14°F) to 80°C (176°F). Power consumption of the electrical devices was monitored with current measurement units by the BMCS.

Mechanical System Identification

Identification of the electrical consumption versus air flow characteristics was a key aspect of optimization of this HVAC system. Example curves for the Direct Photovoltaic-Thermal Supply mode and PCM Charging mode are presented in Figure 3, where electrical power is that provided to the variable speed drive (VSD) unit.

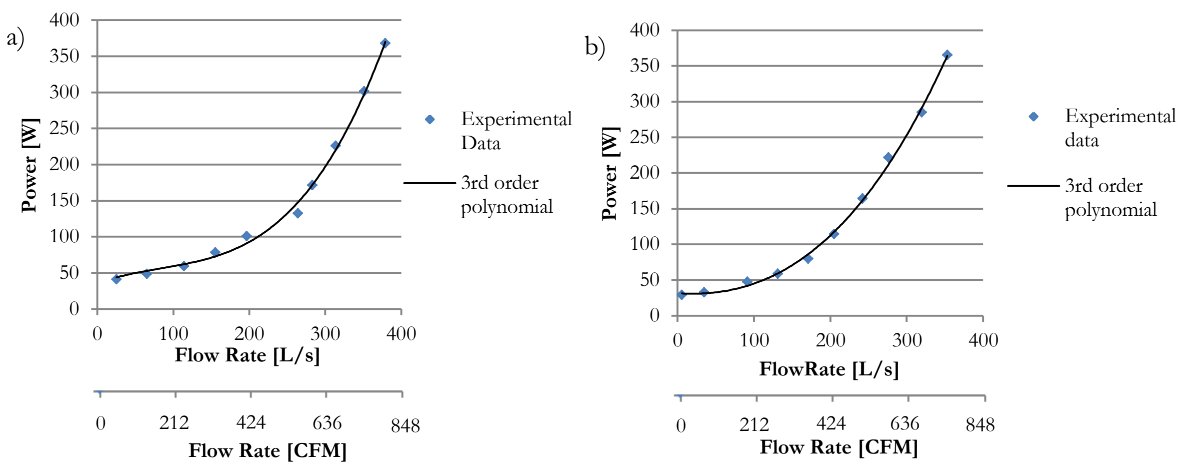

Figure 3: *Variable speed fan power as a function of air flow rate for: a) PVT Direct Supply and b) PCM Charging modes. Note: fan power is the electrical input to the variable speed drive (VSD) unit, which clearly has low efficiency at low fan speeds.*

A third order polynomial has been fitted to the experimental data, since:

$$P_{el} = \frac{\dot{V}}{\eta_f} \cdot \Delta p \qquad (5)$$

Where η_f is the fan efficiency and Δp is the pressure drop, which is proportional to $\dot{V}^2$. Data points have been collected increasing the VSD level controlling the fan from 10% to 100%, in 10% increments. The minimum energy input to the VSD when the fan was operating was approximately 35W. However, when the fan is off the standby power was measured to be approximately 4W. Results from the mechanical system identification have been used to compute the cost function, *C*, together with the predicted supply temperature.

Thermal Performance Results

Figure 4 shows the system operated under the PVT Direct heat supply mode, where T_{avg} is the average temperature of the house, Tout the outside temperature, COP PVT Heating is the COP of the PVT system when operating, Ghr is the global horizontal radiation, Heating_PVT and Heating_HP are the heating inputs of the PVT and the Heat Pump respectively, P_Fans is the electrical consumption of the PVT Fan. It is noticeable that the PVT system can provide a significant amount of heating (in this test a total of 12.9 kWh was provided to the house), with a peak generation of 3.7 kW. This heating has also been provided with a much higher COP, defined as the ratio between thermal and electrical energy (in the graph is represented by COP PVT Heating data points), than a conventional heat pump, achieving an average COP in this test equal to 13.5 (the total electrical energy use in this test is equal to 0.9kWh).It was also found that the system was correctly modulating the fan speed to achieve a good performance throughout the day.

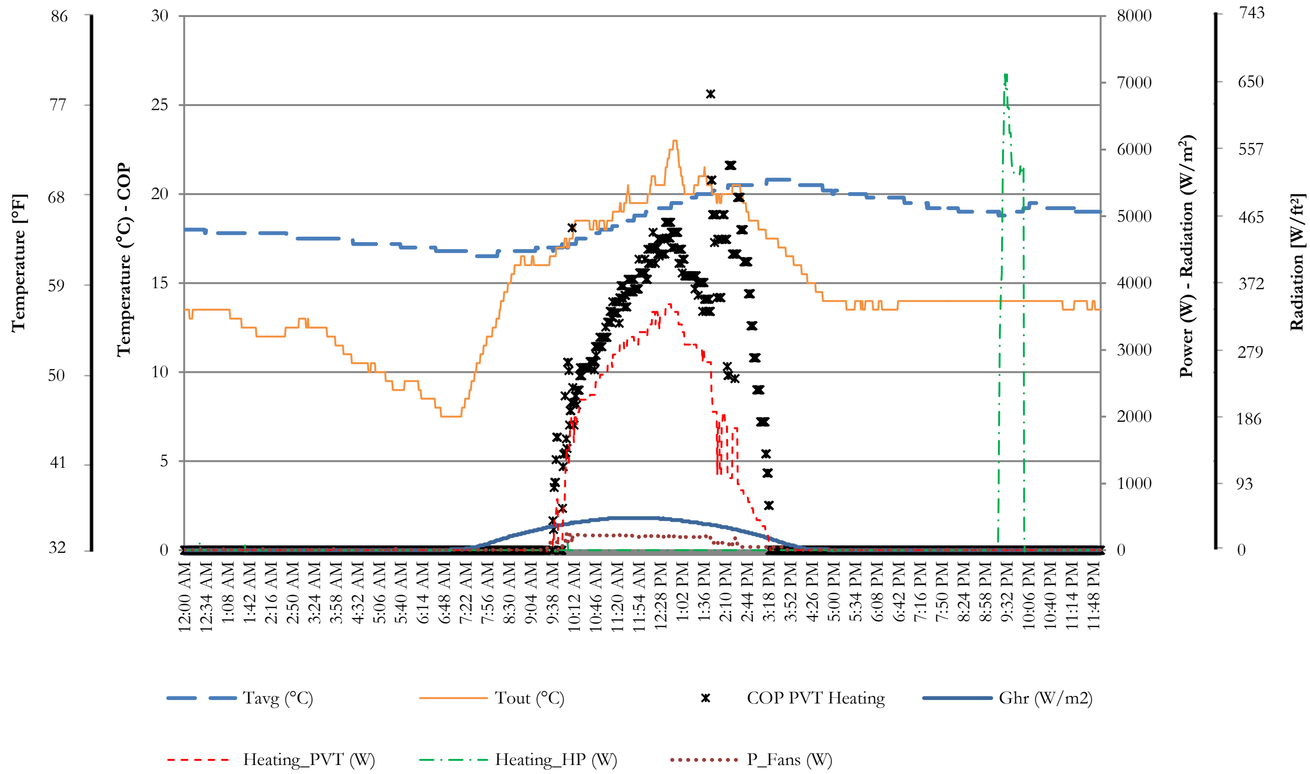

Figure 4: *PVT Direct Supply heating test.*

Figure 5 presents the charging of the PCM thermal energy storage unit, where Tout is the outside temperature, COP PCM Charging is the COP of the PVT system when charging the PCM unit, Ghr is the global horizontal radiation, Heating_to_PCM is the heating stored in the PCM unit, P_Fans is the electrical consumption of the PVT Fan, Tinlet_duct_pcm and Toutlet_duct_pcm are the air temperatures in the ducting at the inlet and the outlet of the PCM unit, Tpcm is the average temperature of the PCM material (average of the measured temperature in the first and last brick of PCM material).

From Figure 5, it can be found that charging the PCM thermal storage unit in a typical winter day, with peak radiation slightly less than 500W/m² (46.45 W/ft²), a total of 26.6kWh have been stored in the PCM unit, with a total electrical energy consumption of 2.5kWh of the fan and an average COP of 10.7.

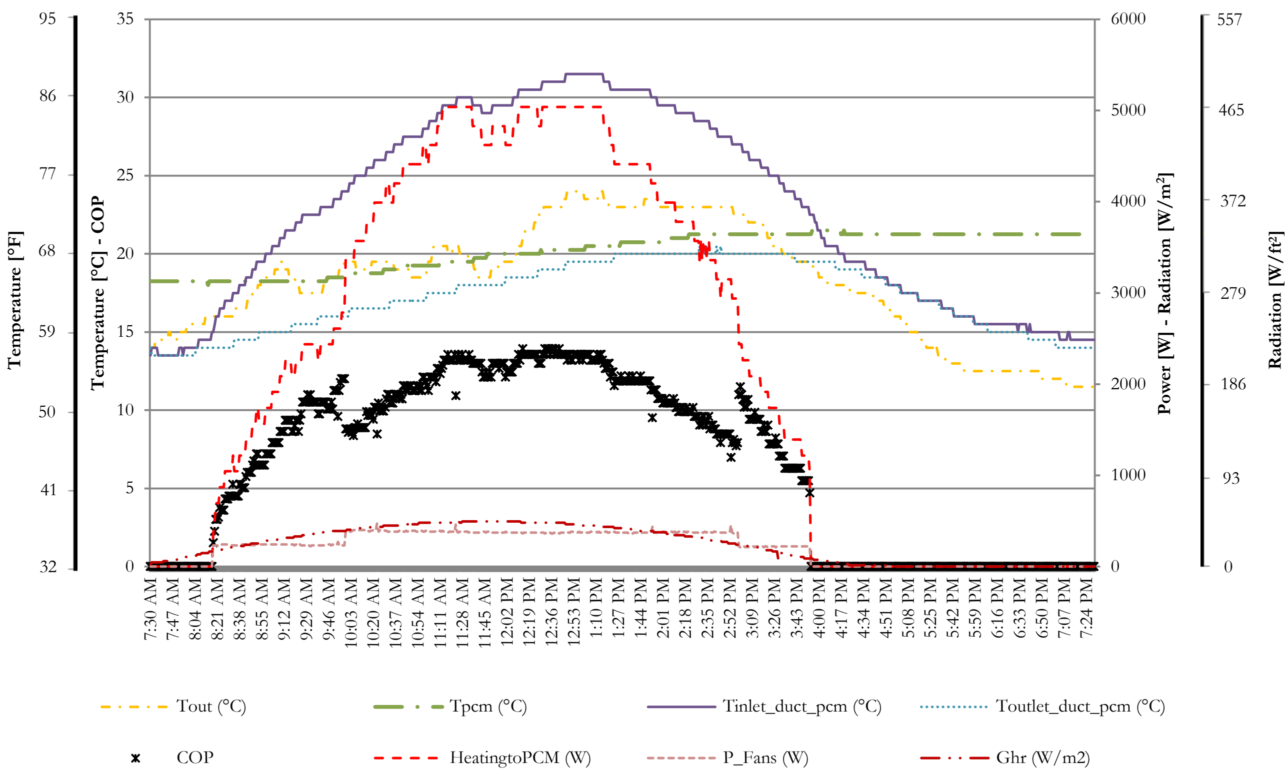

Figure 5: *PCM Charging with PVT test.*

CONCLUSION AND FUTURE WORK

The experimental results presented in this paper showed an encouraging performance of a solar-PVT assisted HVAC system that has been retrofitted to an existing Australian 'fibro' house. The results, that are focused on the performance of the PVT system in heating the building and a PCM thermal energy storage unit, showing that part of the heating demand of the house can be provided at a higher efficiency than the normal air-conditioning system, utilizing the waste heat from the PV panels.

The results showed that when heating directly the house in a typical winter day using the PVT system, this solar assisted HVAC system was capable to achieve a significantly higher efficiency than a commercial air conditioning system, providing 12.9kWh with an average COP of 13.5. The PVT showed a good performance also heating a PCM thermal energy storage unit, storing 26.6kWh with an average COP of 10.7.

The results also showed that an effective control of the flow rate in the system can ensure that the good performance is maintained throughout the day. The complexity of the HVAC system still leaves room for future research on the optimization of the working modes, on which the authors are currently working on, developing model predictive control (MPC) strategies for predicting optimal operational mode and optimizing the controlled variables in order to further improving the energy efficiency of the system.

NOMENCLATURE

P_{th} = heat flow

P_{el} = electrical power consumption of the fan

$\dot{m}$ = mass flow rate

C_p = specific heat capacity of air at 20˚C (68 ˚F)

T_{supply} = supply air temperature

$T_{avg,house}$ = average temperature of the house

Δp = pressure drop

η_f = fan efficiency

α = thermal and electrical energy weighting coefficient

Subscripts

i = discrete flow rate index

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